Nitrogen and phosphorus budgets of the North Atlantic Ocean and its watershed

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Abstract. Anthropogenic food and energy production extensively mobilize reactive nitrogen (N) in the watershed of the North Atlantic Ocean (NAO). There is widespread N distribution by both hydrologic and atmospheric processes within the watershed of the NAO, resulting in reactive N accumulation in terrestrial systems. Net denitrification in most estuaries and continental shelves exceeds the amount of N supplied to the shelves by rivers and requires a supply of nitrate from the open ocean. Thus riverine N is only transported to the open ocean in a few areas with the flow from a few major rivers (e.g., Amazon). Atmospheric N deposition to the open ocean has increased and may increase the productivity of the surface ocean. In addition, as a consequence of increased Fe deposition to the open ocean (due in part to anthropogenic processes), the rate of biological N-fixation may have increased resulting in N accumulation in the ocean. Phosphorus (P) is also mobilized by anthropogenic processes (primarily food production). Relative to N, more of the P is transported across the shelf to the open ocean from both estuaries and major rivers. There are several consequences of the increased availability of N and P that are unique to each element. However, the control on primary productivity in both coastal and open ocean ecosystems is dependent on a complex and poorly understood interaction between N and P mobilization and availability.

Introduction

Nitrogen (N) is a key element of many biogeochemical processes and can be a limiting element of aquatic and terrestrial ecosystem processes (Schlesinger 1991; Vitousek & Howarth 1991). However, about 99% of global N exists as stable atmospheric N₂ (Mackenzie et al. 1993) and thus is unavailable to ecosystems unless it is converted into a reactive N species (reactive N = NH₃, NH₄⁺, organic N, NO, NO₂, HNO₃, NO₃, N₂O₅, HNO₄, HNO₂, NO₂⁻, and NO₃⁻). Once created, one species of reactive N can be converted into other species of reactive N by a variety of chemical and microbial processes. In addition, reactive N species are very mobile via atmospheric and hydrologic pathways. After formation, reactive N can only be converted back to unreactive N₂ by denitrification, an anaerobic process which only occurs
at significant rates in specific types of ecosystems. Reactive N accumulates in the environment if the denitrification rate is less than the rate of N-fixation.

In the absence of humans, natural processes create reactive N by biological N-fixation and lightning. Biological N-fixation occurs in specific microbes when atmospheric N₂ is converted to NH₃ by the enzyme nitrogenase. Lightning produces NO by the reaction of N₂ and O₂ at high temperatures. The former process is about two orders of magnitude greater than the latter on a global basis (Galloway et al. 1995). Human intervention in the N cycle has increased the formation rate of reactive N by fertilizer production, legume and rice cultivation, and combustion of fossil fuels. Results from several recent analyses of the global N cycle (Mackenzie et al. 1993; Ayres et al. 1994; Galloway et al. 1995) generally agree that anthropogenic activities mobilize about 10 Tmol N yr⁻¹ (Tmol = 10¹² moles) and that human activities mobilize N at rates equal to natural terrestrial processes.

There is significant distribution of anthropogenic N by hydrologic and atmospheric transport. Combustion of fossil fuels injects reactive N (NO) directly into the atmosphere. Fertilizer and cultivation N increase the productivity of agricultural landscapes. However, on average, no more than 50% of the applied N fertilizer is removed by crop harvest; the remainder is lost to the atmosphere or hydrosphere, or stored in the soil (Howarth et al. this volume). In addition, N fixed in crops has a short residence time; it is quickly transformed into human or animal waste, which also results in significant inputs to the atmosphere and hydrosphere (Howarth et al. this volume). If the N introduced into the environment by fossil fuel combustion, fertilizer production and cultivation is not denitrified, then reactive N accumulates in downwind or downstream ecosystems.

The mobilization, distribution and accumulation of anthropogenic N impacts a number of physical and ecosystem processes. As discussed in Howarth et al. (this volume), Nixon et al. (this volume), and Michaels et al. (this volume), increased availability of reactive N increases forest productivity, and as a consequence stores atmospheric CO₂, contributes to forest decline (if soil is N-saturated) and climate change, and results in shifts in community structure and ecosystem function. It also increases coastal eutrophication in estuaries (including their wetlands), and results in increased N supply to oligotrophic mid-ocean gyres with concomitant affects on the ecology of the upper ocean. In addition to being important to ecosystems, reactive N also affects atmospheric chemistry (Prospero et al. this volume). High levels of NOₓ (NO + NO₂) play an important role in the photochemical production of O₃ (Moxim et al. 1994). NH₃ is a major source of alkalinity in the atmosphere and a source of acidity in soils (Schlesinger 1991). Although N₂O is not viewed as a reactive form of N in the troposphere, it adsorbs IR